Relationships between Otolith Size and Body Size for Hawaiian Reef Fishes[1]

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Abstract: Estimating body size of fishes from remains recovered from piscivores, archaeological sites, and sedimentary deposits is desirable but rarely accomplished because the relationships between the size of a fish and its durable anatomical structures are largely unknown. Regression equations to predict the size or weight of 41 common Hawaiian reef fishes from sagittae (saccular otoliths) are presented. Data are also grouped into higher taxa to permit size predictions when otoliths cannot be assigned to species.

Animal remains are frequently used to reconstruct faunal assemblages in dietary analysis, archaeology, geology, and paleontology. This work on fishes is difficult because bones and scales can be hard to identify, their numbers may vary among individuals, and the relationship between the size of a bone or scale and the size of the fish that produced it may be unknown.

Otoliths, particularly sagittae or saccular otoliths, may be used to circumvent these problems because they are taxonomically distinct and the number per individual does not vary. Further, they are harder and more durable than skeletal components and are often the only identifiable remains found in geological strata (Rivaton and Bourret 1999). Otoliths are common fossils throughout broad geographic and stratigraphic ranges (Hecht 1990), may be the only evidence that a fish species was present at archaeological sites (Weisler 2002), and are often the only identifiable fish remains found in the stomachs or feces of predators (Hecht 1990). Finally, the size of otoliths can be used to estimate fish size, and a fair number of these relationships have been described for fishes worldwide (Frost and Lowry 1981, Echevierria 1987, Gamboa 1991, Plötz et al. 1991, Smale et al. 1995, Granadeiro and Silva 2000, Harvey et al. 2000, Mikkelsen et al. 2002, Naya et al. 2002, Waessle et al. 2003).

No large-scale analysis of otolith-fish size relationships has been conducted for Hawaiian fishes. With 1,250 species of which 22.3% of coastal species are endemic (Mundy 2005), this information is needed for research on resource use by early Hawaiians, dietary analysis of piscivores, and reconstruction of ancient marine environments. Here I present analyses of the relationship between otolith length and fish length or weight. These results complement a guide to the identification of Hawaiian fish otoliths (Dye and Longenecker 2004).

MATERIALS AND METHODS

Fishes were collected from May 2000 through September 2002 from the forereef of Kāne'ohe Bay. Collecting area boundaries were the 5.5 m isobath shoreward (parallel to

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the barrier reef), the 30.5 m isobath seaward (the bottom of a drop-off at the mouth of the bay), and boating channels laterally. All specimens were identified, then standard length (in millimeters) and total body weight (in grams) were measured. Sagittae were removed and stored dry in tissue culture plates, with one species per plate and one individual per well. One otolith per fish was haphazardly chosen (or the lone otolith if one was broken or missing) and measured with digital calipers along the rostrum to postrostrum axis (nomenclature of Secor et al. [1992]).

Least squares regression analysis of otolith length versus standard length and otolith length versus total body weight was performed for each species. Data were also combined to search for the same relationships within all higher taxa. Equations are presented only for regressions with $P < .5$.

RESULTS AND DISCUSSION

Standard length can be modeled as a linear function of otolith length (Appendix 1), and total body weight can be predicted using a power function of otolith length (Appendix 2). For all but two cases, the otolith-weight relationships could be modeled with two parameters. The exceptions were three-parameter power functions.

Both appendixes are organized phylogenetically. Species included in supraspecific analyses are either annotated at the end of the appendix (for space considerations) or listed parenthetically adjacent to taxon name if no significant relationship was found for that species alone. Species with significant otolith-fish size relationships are listed along with their regression equations below the supraspecific taxon heading. For example, results for the length regression of the subfamily Pomacentrinae (Appendix 1) include four species: *Stegastes marginatus*, which did not yield a significant regression on its own, listed parenthetically beside the subfamily name; *Abudefduf abdominalis*, which did have a significant relationship, listed below the subfamily name; and *Plectroglyphidodon imparipennis* and *P. johnstonianus*, indicated by an annotation to the generic name. A significant regression could not be constructed for either species alone; however, a genus-level relationship was significant.

This phylogenetic grouping serves three purposes. First, it can be used to predict the size of a fish from otoliths larger or smaller than those used in the analyses. Although linear relationships with high coefficients of determination, such as many of those in Appendix 1, might reasonably be used for extrapolation, doing so with curvilinear relationships (Appendix 2) is likely to provide unrealistic estimates. Using a relationship for a higher taxon, based on a wider size range of individuals, may help avoid the need for extrapolation. Second, because otoliths are more easily assigned to higher taxa than to species, the groupings provide reasonable predictions of fish size when a species-level identification of an otolith is not feasible. The more-general higher-taxa regressions should be used in such cases. Third, these groups also provide predictions for species not included in the analysis. With 1,250 fishes known from Hawai‘i, the equations presented here represent just a fraction of the work necessary for detailed reconstruction of fish assemblages. In the interim, these higher-taxa relationships may suffice for predicting fish sizes.

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Appendix 1

Results of Linear Regression of Otolith Length (OL) versus Standard Length (SL), in millimeters [$SL = a + b(OL)$]

Taxon	*n*	Range (mm)	*a*	*b*	r^2
Anguilliformes					
Muraenidae					
Gymnothorax[a]	17	1.48–6.03	−152.2564	191.6527	0.89
Aulopiformes					
Synodontidae					
Synodus[b]	4	0.62–1.09	−8.1623	54.6525	0.96
Beryciformes					
Holocentridae (*Myripristis berndti*)	27	3.95–9.66	58.3229	11.2756	0.77
Sargocentron[c]	16	3.95–8.85	13.4202	20.4562	0.81
Myripristis kuntee	8	7.34–9.66	80.4908	8.5006	0.57

Appendix 1 (continued)

Taxon	*n*	Range (mm)	*a*	*b*	r^2
Gasterosteiformes					
Syngnathoidei (*Fistularia commersonii*)	15	1.76–4.44	21.3819	185.1548	0.74
Aulostomus chinensis	13	1.76–2.47	−139.8717	264.7553	0.53
Scorpaeniformes					
Scorpaenidae					
Scorpaenodes (*hirsutus*)	34	1.17–3.00	−0.9014	13.3501	0.91
kelloggi	28	1.17–2.47	−1.1135	13.5516	0.95
Sebastapistes	34	1.30–4.22	−7.1377	18.7071	0.99
coniorta	18	2.52–4.22	−13.4726	20.9575	0.94
fowleri	6	1.40–1.71	−3.4567	16.0512	0.99
galactacma	10	1.30–2.86	−4.0268	17.0121	0.99
Perciformes					
Cirrhitoidei					
Cirrhitidae (*Cirrhitops fasciatus*)	89	1.70–7.17	−28.1050	33.5819	0.96
Amblycirrhitus bimacula	18	1.70–2.78	−12.4234	27.1491	0.95
Cirrhitus pinnulatus	23	4.01–7.17	−39.9257	36.7757	0.90
Paracirrhites	43	1.74–5.32	−35.1914	35.2619	0.94
arcatus	18	1.74–3.88	−22.9247	30.0187	0.98
forsteri	25	2.41–5.32	−40.1079	37.5093	0.90
Percoidei					
Apogonidae					
Apogoninae	11	1.34–8.00	−6.8884	14.5747	0.94
Apogon erythrinus	7	1.34–3.56	−1.2863	11.5146	0.99
Pristiapogon (*kallopterus*, *taeniopterus*)	4	3.78–8.00	−40.1918	22.5921	1.00
Serranidae					
Cephalopholis argus	67	6.02–10.34	−192.4328	58.6273	0.85
Plectranthias nanus	6	1.86–2.70	7.4999	10.5065	0.99
Pseudogramma polyacanthum	9	0.88–2.96	−0.7907	18.1518	0.99
Carangidae[d]	7	1.56–13.31	144.2950	36.0742	0.78
Lutjanidae					
Lutjanus kasmira	16	7.58–9.97	87.3414	11.1229	0.57
Mullidae	74	2.27–5.14	−78.1329	71.6053	0.90
Mulloidichthys (*flavolineatus*, *vanicolensis*)	4	3.12–4.74	−186.6056	94.5660	0.99
Parupeneus (*insularis*)	70	2.27–5.14	−75.7908	71.3657	0.92
cyclostomus	9	2.37–5.14	−94.5359	78.5276	0.97
multifasciatus	33	2.48–4.13	−67.5846	69.2349	0.91
pleurostigma	7	2.27–4.17	−112.3948	87.3023	0.93
porphyreus	18	2.41–4.63	−84.3878	71.4596	0.97
Chaetodontidae[e]	40	2.32–5.43	−21.7420	33.1154	0.79
Chaetodon[f]	31	3.29–5.43	−9.2852	29.1519	0.87
multicinctus	8	3.33–4.01	25.0728	18.8563	0.76
Labroidei					
Labridae					
Bodianus albotaeniatus	32	2.34–8.32	−28.3960	41.3056	0.96
Cheilininae[g]	4	0.83–2.89	−3.5213	27.0441	0.99
Corinae[h]	70	0.46–5.06	−15.6196	50.4776	0.95
Anampses cuvier	6	2.57–3.84	−58.8524	77.1388	0.99
Coris (*flavovittata*, *gaimard*)	15	1.56–4.43	−47.5676	66.9298	0.91
venusta	11	1.69–2.26	−59.0002	72.2014	0.81
Thalasomma	43	0.46–5.06	−12.6037	49.2495	0.97
ballieui	23	2.06–5.05	−13.7798	54.7471	0.92
duperrey	19	0.46–3.53	−7.4138	42.1491	0.99
Pomacentridae	53	1.24–6.75	−13.3273	24.5819	0.92
Chrominae	36	1.24–6.75	−10.9624	23.1550	0.94
Chromis (*hanui*, *ovalis*)	25	1.24–6.75	−5.5540	20.1414	0.91
vanderbilti	19	1.24–2.47	−2.6341	19.1729	0.93

Appendix 1 (continued)

Taxon	*n*	Range (mm)	*a*	*b*	r^2
Dascyllus albisella	11	3.57–4.07	−30.1740	29.9936	0.59
Pomacentrinae (*Stegastes marginatus*)	17	1.76–5.64	−14.5262	26.2209	0.89
Abudefduf abdominalis	8	4.66–5.64	−2.1212	27.4818	0.73
Plectroglyphidodon[i]	6	1.76–3.41	9.0694	16.2063	0.84
Scaridae					
Chlorurus (*perspicillatus*, *spilurus*)	5	4.63–8.40	−172.2770	74.4305	0.95
Trachinoidei					
Pinguipedidae					
Parapercis schauinslandii	8	2.79–3.68	1.6896	22.3855	0.93
Blennioidei[j]	119	0.23–2.09	7.5063	14.6156	0.47
Blenniidae					
Salariini (*Exallias brevis*, *Cirripectes quagga*)	57	0.41–2.09	3.6530	27.6834	0.95
Cirripectes vanderbilti	22	0.79–2.09	−1.2033	30.0014	0.98
Entomacrodus strasburgi	32	0.41–0.85	0.3729	33.7774	0.93
Tripterygiidae					
Enneapterygius atriceps	61	0.30–1.45	5.6105	13.5322	0.94
Gobioidei					
Gobiidae					
Gobiinae (*Coryphopterus duospilus*)	128	0.26–2.55	4.8242	14.9124	0.73
Eviota (*susanae*)	86	0.26–0.62	0.7472	24.4057	0.77
epiphanes	79	0.26–0.62	0.6536	24.5277	0.77
Priolepis	11	0.45–0.97	2.5390	14.7486	0.90
eugenius	6	0.45–0.96	3.2763	13.7504	0.84
farcimen	5	0.54–0.97	1.7377	15.8309	0.97
Trimma unisquamis	29	0.44–0.86	1.4097	19.7362	0.84
Acanthuroidei					
Acanthuridae					
Acanthurinae	43	1.43–5.21	−9.3721	29.2571	0.77
Acanthurus[k]	28	2.32–5.08	−23.0534	34.4433	0.61
nigrofuscus	7	3.24–4.81	−13.3996	26.6374	0.91
triostegus	12	2.66–3.88	−87.1491	60.8449	0.93
Ctenochaetus strigosus	10	3.80–5.21	−43.8559	33.2044	0.81
Zebrasoma flavescens	5	1.43–3.88	−30.9091	41.7762	0.97
Tetraodontiformes					
Tetraodontoidei					
Tetraodontidae					
Canthigasterinae					
Canthigaster (*amboinensis*, *coronata*)	17	0.76–1.30	−6.7212	56.7368	0.67
jactator	12	0.87–1.24	−7.1636	54.9559	0.75

[a] *G. eurostus*, *G. flavimarginatus*, *G. melatremus*, *G. meleagris*, *G. undulatus*.
[b] *S. dermatogenys*, *S. ulae*, *S. usitatus*.
[c] *S. diadema*, *S. punctatissimum*, *S. spiniferum*.
[d] *Carangoides orthogrammus*, *Caranx ignobilis*, *C. melampygus*, *Decapterus macarellus*, *Scomberoides lysan*, *Seriola dumerili*.
[e] *Forcipiger flavissimus*, *F. longirostris*, *Hemitaurichthys polylepis*, *Heniochus diphreutes*.
[f] *C. fremblii*, *C. kleinii*, *C. lunula*, *C. lunulatus*, *C. miliaris*, *C. ornatissimus*, *C. quadrimaculatus*, *C. unimaculatus*.
[g] *Oxycheilinus bimaculatus*, *Pseudocheilinus evidanus*.
[h] *Gomphosus varius*, *Halichoeres ornatissimus*, *Macropharyngodon geoffroy*, *Pseudojuloides cerasinus*, *Stethojulis balteata*.
[i] *P. imparipennis*, *P. johnstonianus*.
[j] *Enchelyurus brunneolus*, *Plagiotremus ewaensis*, *P. goslinei*.
[k] *A. leucopareius*, *A. nigroris*, *A. olivaceus*, *A. xanthopterus*.

Appendix 2

Power Functions for Otolith Length (OL) in millimeters versus Total Body Weight (wt) in grams [wt = $a(\mathrm{OL})^b$]

Taxon	*n*	Range (mm)	*a*	*b*	r^2
Anguilliformes					
Muraenidae					
Gymnothorax[a]	17	1.48–6.03	14.4055	3.0224	0.69
Aulopiformes					
Synodontidae					
Synodus (*dermatogenys*, *ulae*, *usitatus*)	4	0.62–1.09	1.1265	4.7862	1.00
Beryciformes					
Holocentridae (*Myripristis berndti*, *M. kuntee*)	20	4.02–9.66	2.1109	1.9932	0.26
Sargocentron (*punctatissimum*, *spiniferum*)	10	4.02–8.85	0.0024	5.6832	0.99
diadema	6	5.32–6.24	0.0446	3.9981	0.71
Gasterosteiformes					
Aulostomidae					
Aulostomus chinensis	11	1.76–2.47	0.8205	7.0540	0.69
Scorpaeniformes					
Scorpaenidae					
Scorpaeninae (*Scorpaenopsis cacopsis*)	61	1.17–11.95	1.7142	2.9535	0.97
Scorpaenodes (*hirsutus*)[b]	33	1.17–3.00			0.71
kelloggi[c]	27	1.17–2.47			0.76
Sebastapistes (*ballieui*, *fowleri*)	25	1.30–4.22	0.0342	4.5055	0.99
coniorta	9	2.62–4.22	0.0371	4.4469	0.99
galactacma	10	1.30–2.86	0.0602	3.8583	0.97
Perciformes					
Cirrhitoidei					
Cirrhitidae (*Cirrhitops fasciatus*)	65	1.70–7.17	0.2186	3.9380	0.91
Amblycirrhitus bimacula	18	1.70–2.78	0.1509	3.8199	0.82
Cirrhitus pinnulatus	17	4.01–7.17	0.4187	3.5905	0.75
Paracirrhites	27	1.74–5.32	0.0026	6.7255	0.90
arcatus	6	1.74–3.88	0.2317	3.4181	0.97
forsteri	21	2.41–5.32	0.0024	6.7632	0.87
Percoidei					
Apogonidae					
Apogoninae (*Pristiapogon kallopterus*)	8	1.34–3.78	0.0603	2.7928	0.98
Apogon erythrinus	7	1.34–3.56	0.0511	2.9434	0.97
Serranidae	73	0.88–10.34	0.0216	4.9885	0.94
Anthiinae					
Plectranthias nanus	6	1.86–2.70	0.0475	3.2849	0.76
Epinephelinae[d]	67	0.88–10.34	0.0216	4.9885	0.94
Cephalopholis argus	57	6.02–10.34	0.0219	4.9821	0.92
Carangidae[e]	7	1.56–13.31	14.5222	2.4626	0.88
Lutjanidae					
Lutjanus kasmira	15	7.58–9.97	0.6549	2.5485	0.40
Mullidae	63	2.27–5.14	0.0584	5.9335	0.85
Mulloidichthys (*flavolineatus*, *vanicolensis*)	4	3.12–4.74	0.6340	3.9364	0.94
Parupeneus (*insularis*)	59	2.27–5.14	0.0603	5.9518	0.91
cyclostomus	9	2.37–5.14	0.0084	7.1835	0.97
multifasciatus	26	2.48–4.13	1.1399	3.7126	0.56
pleurostigma	4	2.27–4.17	0.2976	4.8780	0.99
porphyreus	17	2.41–4.63	0.9420	4.0462	0.81
Chaetodontidae[f]	35	2.32–5.43	0.1968	4.1501	0.91
Chaetodon[g]	27	3.29–5.43	0.1907	4.1700	0.91
multicinctus	8	3.33–4.01	7.1037	1.3805	0.51
Labroidei					
Labridae					
Bodianus albotaeniatus	19	4.36–8.19	1.5694	3.1149	0.64
Cheilininae[h]	4	0.83–2.89	0.3264	3.5396	0.98
Corinae[i]	54	0.46–5.06	2.0786	3.5165	0.83

Appendix 2 (continued)

Taxon	*n*	Range (mm)	*a*	*b*	r^2
Anampses cuvier	5	2.57–3.84	1.4503	4.2652	0.96
Coris (*flavovittata*, *gaimard*)	14	1.56–4.43	5.9694	2.7620	0.81
venusta	10	1.69–2.26	0.5245	4.7119	0.81
Thalasomma	30	0.46–5.06	0.4435	4.5112	0.90
ballieui	18	2.06–5.05	0.6992	4.2145	0.82
duperrey	11	0.46–3.44	3.6409	2.2297	0.85
Pomacentridae					
Chrominae					
Chromis (*hanui*, *ovalis*)	23	1.24–6.75	0.9579	2.3661	0.78
vanderbilti	18	1.24–2.47	0.0843	4.1649	0.86
Dascyllus albisella	7	3.57–3.95	0.0651	4.8391	0.73
Pomacentrinae (*Stegastes marginatus*)	14	1.76–5.64	0.0984	4.3794	0.94
Abudefduf abdominalis	8	4.66–5.64	0.5028	3.4101	0.70
Plectroglyphidodon[j]	6	1.76–3.41	0.2636	3.3531	0.97
Scaridae[k]	6	4.63–8.40	6.5119	3.0414	0.85
Trachinoidei					
Pinguipedidae					
Parapercis schauinslandii	7	2.79–3.68	0.0991	3.7647	0.90
Blennioidei[l]	115	0.23–2.09	0.1232	6.2899	0.77
Blenniidae					
Salariini (*Exallias brevis*, *Cirripectes quagga*)	57	0.41–2.09	0.2575	5.2060	0.76
Cirripectes vanderbilti	22	0.79–2.09	0.7362	3.1971	0.97
Entomacrodus strasburgi	32	0.41–0.85	0.7141	3.2908	0.87
Tripterygiidae					
Enneapterygius atriceps	57	0.30–1.45	0.1281	2.4773	0.90
Gobioidei					
Gobiidae	128	0.26–2.55	0.1330	2.3381	0.96
Gobiinae (*Coryphopterus duospilus*)	127	0.26–2.55	0.1333	2.3363	0.96
Eviota (*susanae*)	84	0.26–0.62	0.2772	2.9737	0.54
epiphanes	73	0.26–0.62	0.2655	2.7889	0.76
Priolepis (*farcimen*)	11	0.45–0.97	0.0997	3.2523	0.76
eugenius	6	0.45–0.96	0.1099	3.1213	0.88
Trimma unisquamis	30	0.44–0.86	0.1853	3.6008	0.27
Acanthuroidei					
Acanthuridae					
Acanthurus[m]	20	2.32–5.08	3.2123	2.4737	0.32
nigrofuscus	6	3.34–4.56	0.3143	3.4034	0.74
triostegus	7	2.66–3.88	0.1381	5.1965	0.76
Ctenochaetus strigosus	9	3.80–5.21	0.4840	3.3061	0.71
Tetraodontiformes					
Tetraodontoidei					
Tetraodontidae					
Canthigasterinae					
Canthigaster (*amboinensis*, *coronata*)	17	0.76–1.30	8.2161	3.3290	0.56
jactator	12	0.87–1.24	7.0020	3.1480	0.58

[a] *G. eurostus*, *G. flavimarginatus*, *G. melatremus*, *G. meleagris*, *G. undulatus.*
[b] $Wt = 0.1150 + 0.0325(OL)^{3.6323}$.
[c] $Wt = -0.0469 + 0.0602(OL)^{3.2297}$.
[d] *Liopropoma collettei*, *Pseudogramma polyacanthum.*
[e] *Carangoides orthogrammus*, *Caranx ignobilis*, *C. melampygus*, *Decapterus macarellus*, *Scomberoides lysan*, *Seriola dumerili.*
[f] *Forcipiger flavissimus*, *F. longirostris*, *Hemitaurichthys polylepis*, *Heniochus diphreutes.*
[g] *C. fremblii*, *C. kleinii*, *C. lunula*, *C. lunulatus*, *C. miliaris*, *C. ornatissimus*, *C. quadrimaculatus*, *C. unimaculatus.*
[h] *Oxycheilinus bimaculatus*, *Pseudocheilinus evidanus.*
[i] *Gomphosus varius*, *Halichoeres ornatissimus*, *Macropharyngodon geoffroy*, *Pseudojuloides cerasinus*, *Stethojulis balteata.*
[j] *P. imparipennis*, *P. johnstonianus.*
[k] *Calotomus carolinus*, *Chlorurus perspicillatus*, *C. spilurus.*
[l] *Enchelyurus brunneolus*, *Plagiotremus ewaensis*, *P. goslinei*
[m] *A. leucoparieus*, *A. nigroris*, *A. olivaceus*, *A. xanthopterus.*